AN APPLICATION OF THE LEGO PACKAGE TO PWR POWER PLANT MODELLING

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Abstract. The LEGO package is a modular simulation code particularly oriented to a detailed description of power generation plants for dynamic dimensioning verification, control system design and operational procedures verification. In this paper, after a brief survey of the package features, a PWR power plant model and some significant validation tests are presented. ENEL (the Italian National Electricity Board) is now using this model within the frame of the Italian National Nuclear Energy Program.

Keywords. Digital computer applications; dynamics; nuclear plant; nuclear reactors; steam generators; modelling.

INTRODUCTION

Since 1981 the LEGO package is operational and it has been used in several applications (Maffezzoni et al., 1983), (Corno et al., 1983).

It is a modular package developed at the Research and Development Department of the Italian National Electricity Board (CRA-ENEL) for modelling and simulation of continuous processes, particularly oriented to large size electrical generating plants. The package is conceived to carry out the whole pattern of a simulation study from the plant data input to the graphic presentation of the simulation results.

Moreover, it is equipped with special outputs for the interface with control design programs.

Lego has been already successfully validated with respect to experimental trials on conventional power plants (Marcocci and Spelta, 1983).

This paper deals with a new application of Lego for the simulation of the operational and incidental transients of the Italian Westinghouse-type pressurized water reactors (PWR) which are now in the design phase.

ENEL plays the role of architect engineer, while NIRA representing Italian industry is in charge of the NSSS design under Westinghouse license (three loops 1000 MW plants).

The model, made by Lego and named SFINCS, will be mainly used for the following purposes:

- components dimensioning dynamic verification;
- control and protection systems verification and parameters tuning;
- safety margins verification.

The setting-up of the model SFINCS has required the construction of some typical nuclear power plant modules. These have been set-up in the frame of a collaboration between CRA and the Electricité de France Design Service (SEPTEN), thanks to SEPTEN's large experience in PWR plants.

After a brief description of the main features of the package Lego the paper presents the model SFINCS and its satisfactory validation.

ENEL is now using SFINCS as well as another similar model named STRIP, set-up by means of the modular EDF code SICLE (Maxant and Perrin, 1979) (Busi et al., 1983), for the sake of an independent verification of critical transients studies.

THE LEGO PACKAGE

Mathematical models and computer simulation of large power plants are currently used for many purposes such as process design assessment, operating procedures evaluation, prediction of incident effects and control system evaluation and design. Dealing with very complex processes such as large power plants, the construction of full-scope mathematical models for real case studies generally requires considerable engineering and software work.

At CRA, a positive solution of such a problem has been searched for by developing the Lego package which is able to support the user in carrying out the model and simulation studies, thus it could be better defined as a package for "Computer Aided Modelling".

The LEGO package consists of a "modules library" constituted of mathematical models of elementary components and of a "master program" which allows the user to build-up his model by automatically assembling subsets of equations and solving the numerical problem.

The peculiar aspects of the Lego package, described in a previous paper (Marcocci and Spelta, 1983), can be summarized as follows:

modularity - power plant processes are essentially modular in that they are composed of many elements of relatively few types. This fact has been exploited by the package that allows the user to set-up an overall plant model

flexibility - the user can solve special modelling applications by developing for himself the mathematical model of special components which can be included in the "modules library" of the package and computationally treated as a standard library module.

reliability - all the numerical algorithms used by the package are centralized in the "master program". The updating of mathematical modelling assumptions in a module does not require an updating of the numerical algorithmes. Moreover the modules can exchange information among themselves only by means of the "master program" so that they can be considered independent.

A module is a lumped parameters mathematical model describing a physical process by means of a non-linear algebraic and differential equations subsystem of this form:

$$\dot{x}_n = f_n(x_n, y_m, u_p) \tag{1}$$

$$0 = g_m(x_n, y_m, u_p) \tag{2}$$

where x_n, y_n are the vectors of the differential (state) and algebraic outputs respectively and u_p is the vector of input variables.

A distinctive feature of Lego is that the user is allowed to build-up the model of a real process by simply describing the connections among process subsystems (i.e. the topology).
Topological data are constitued of the module names (blocks) selected by the user and of a list of conventional names (labels) attributed to the input and output variables of the modules.

Physical and mathematical interconnections between two blocks are established when the same label is used to define an output variable of one block and an input variable of the other.

It must be noticed that the user is not required to write a program in order to describe the overall equations system, the solution of which is carried out by the "master program" in a suitable interaction mode with the "modules library". The main features of the LEGO package with respect to the numerical problem can be here summarized as follows:

- simultaneous solution of all non-linear algebraic and differential equations using an implicit formula for the numerical integration method.
- use of sparse matrix techniques in order to reduce computation time dealing with large power plant overall models.
- steady-state computation allowing interchange of the role of input variables, output variables and uncertain constant parameters.
- linearized model matrix computation which can be used as input data for control design programs.

Furthermore, the model building is computer aided by suitable interactive debugging in all the input data phases and by flexible graphic programs for the presentation of simulation results.

PWR POWER PLANT SFINCS MODEL

The plant considered in this application is a 900 MW pressurized water reactor (PWR) of Westinghouse-type. The main components of the nuclear steam supplying system (NSSS) are the reactor core, the pressurizer, three primary loops with three primary pumps and three steam generators. .
The balance of plant (BOP) normally includes the turbine, the moisture separators-reheaters, the condenser, the feedwater heaters, the deaerator, the feedwater pumps.

In order to satisfy the purposes underlined in the introduction of this paper, some important reductions of the real power plant have been applied to obtain the model; the most important one is the equivalent primary loop adopted where only one reactor coolant pump and one steam generator are considered.

In the SFINCS model layout (Fig. 1) it is possible to note that the BOP is particularly detailed in order to represent all those components which can be under dynamic dimensioning verification or can be actuated by control and protection systems.

The main characteristics of NSSS represented in the SFINCS model are:

- zero dimensional kinetics using six groups of delayed neutrons
- a lumped parameters model of the cylindrical fuel rod in which the axial power shape is assumed constant during a transient
- a single phase lumped parameters model of the equivalent primary circuit
- a non equilibrium thermodynamics approach in the treatment of steam and water in the pressurizer
- a lumped parameters model of the steam generator where U-tubes (primary circuit), down-comer, riser and drum are detailed.

The main characteristics of BOP components can be summarized as follows:

- valves are treated with a model allowing the most general conditions of the fluid (steam, water or mixture)
- water and steam tubes are treated with suitable lumped parameters models
- a non equilibrium thermodynamics approach is used in HP-Heaters and deaerator models.

It must be noticed that the low pressure part of BOP is represented by suitable simplified boundary conditions imposed to the deaerator model which is an important storage of energy.

Several control systems of the NSSS and BOP are represented in SFINCS, including the rod control system, the pressurizer level and pressure control system, the steam generator level control system, the steam dump control system, the feedwater pump speed control system and the deaerator level control system.

A control system can be implemented in the LEGO package in two ways:

(i) by a module of the process included in the package library;
(ii) by using a special feature of the Lego package that allows boundary condition assignments during transient computation.

Adopting (i), the control system is computationally treated by the "master program" in an implicit method as a standard module of the library which describes a part of the process.

Adopting (ii), the control system is one step delayed with respect to the process computation. In (i), the integration time step has no influence on the numerical stability, while the choice of (ii) reduces the intrinsic stability quality of the numerical integration method of the LEGO package.

To support the user in a control system module implementation, some typical components of regulation systems like filter, lead-lag, integrators, etc. have been developed and introduced in the "modules library".
It must be noticed that control systems implemented by using (ii) can simulate a real

microprocessor control system which normally works with a delay of a finite time-step with respect to the process. Due to the adoption of the Integrated Protection and Control System in the Italian PWR power plant program, it has been thought useful to represent in SFINCS all the control systems with (ii).

The dimensions of the SFINCS mathematical model depend mainly upon the number of meshes used to represent NSSS and BOP. In particular, 9 meshes (axial and radial) are used for fuel rods, 24 meshes for the primary circuit with U-tubes, 12 meshes for the down-comer and riser of the steam generator, 22 meshes for feedwater and steam pipe lines. The total number of equations, excluding boundary conditions and control systems, is 350. They are solved simultaneously by Lego at each time-step.

The SFINCS model is implemented on a VAX mini computer 11/750 in service at CRA. About 20 seconds is the medium CPU time required for 1 second of a severe transient simulation (e.g. the first 7 minutes of a full-load rejection).

With the aim to have a model which can be considered reliable in control and protection system design studies and in operational procedures verification, a comparison between a real power plant transient and the SFINCS model responses was necessary.

A worthwhile collaboration on PWR power plant modelling involving CRA and Electricité de France Design Service (SEPTEN) offered the opportunity to compare SFINCS model transient responses with an experimental power plant transient used by SEPTEN for BABEL code validation (Ourmann and Pelin, 1981).

For this purpose, geometrical data and control systems of SFINCS were adapted at a French power plant and some modelling principles were assumed, taking advantage of the wide SEPTEN experience in the development of simulation tools.

The power plant transient assumed as a reference test is a manual full-load rejection, that can be considered the most important transient among normal operation procedures because it allows a

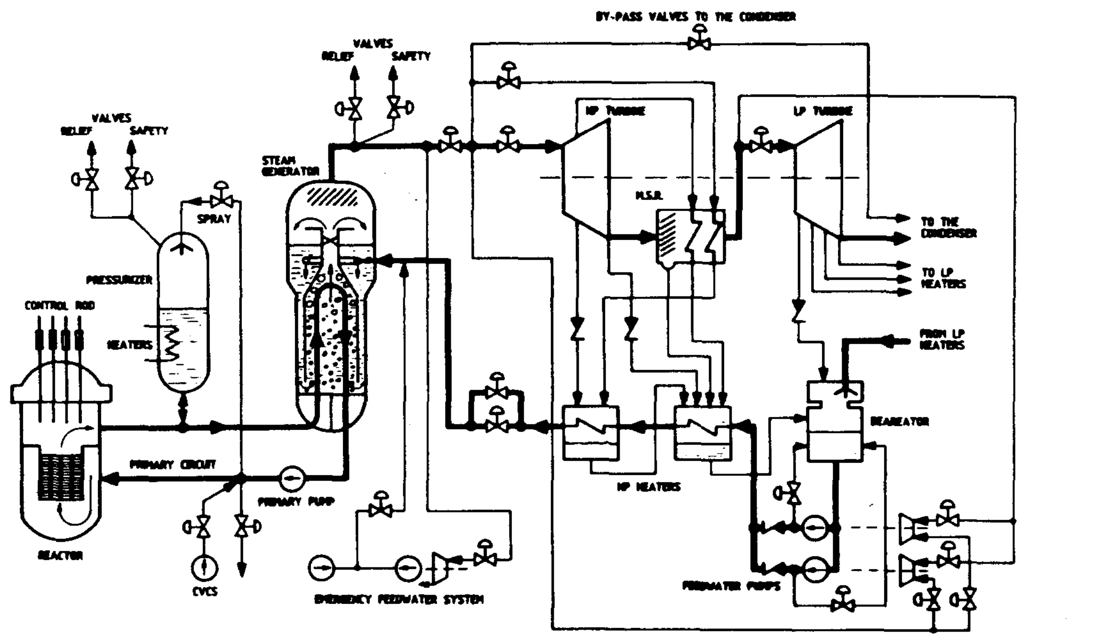

FIG. 1. SFINCS model scheme.

SFINCS MODEL VALIDATION

As mentioned in the introduction of this paper, the setting-up of the SFINCS model required the development of some nuclear power plant modules that are now included in the "modules library". Before the validation of the complete model described above, some significant tests on single modules have been executed in order to verify modelling hypotheses and software reliability.

These tests were performed easily by exploiting the distinctive modular quality of the LEGO package; the reference tests used in this phase were obtained by codes BABEL and SICLE used at Electricité de France. In this way some important components like the core (including kinetics, fuel rods, antireactivity effects and the moderator), the pressurizer and the steam generator were validated from the physical point of view.

complete test upon all the regulation systems.

Following the opening of the line-breakers, the main turbine must immediately reduce its nominal power to prevent mechanical overspeed and to supply only electrical auxiliary systems. Thermal power produced by the reactor must be evacuated mainly to the condenser, thus actuating an immediate opening of the steam dump system valves. All control systems operate in order to reduce nuclear and thermal power up to a minimum load and to avoid a reactor trip or a protection system intervention.

The first comparison test was on steady state computation which showed some important difficulties in obtaining the exact initial conditions to start the transient because:

- the real three primary loops were not at the same hot and cold temperatures (the maximum of

these is normally used as the controlled variable for the rod control system);
- the steam generators input and output massflow rate balance showed some measurement errors;
- the feedwater temperature measured at the steam generators inlet was considerably incorrect.

For these reasons, the power plant steady-state computed by SFINCS, solving all the balance equations with a strict tolerance and assumed as an initial condition for the load rejection transient, is a necessary compromise with regard to the reliability of measurements.

The transients comparison is presented in Fig. 2 and denotes a general favorable agreement of SFINCS to power plant behaviour. It is worth noticing that control system parameters have a big influence on transient responses so that the knowledge of the real control system parameter setting becomes necessary when some modelling principles are being verified.

The main experience derived from this validation test is that, when dealing with controlled processes, the implementation of regulation

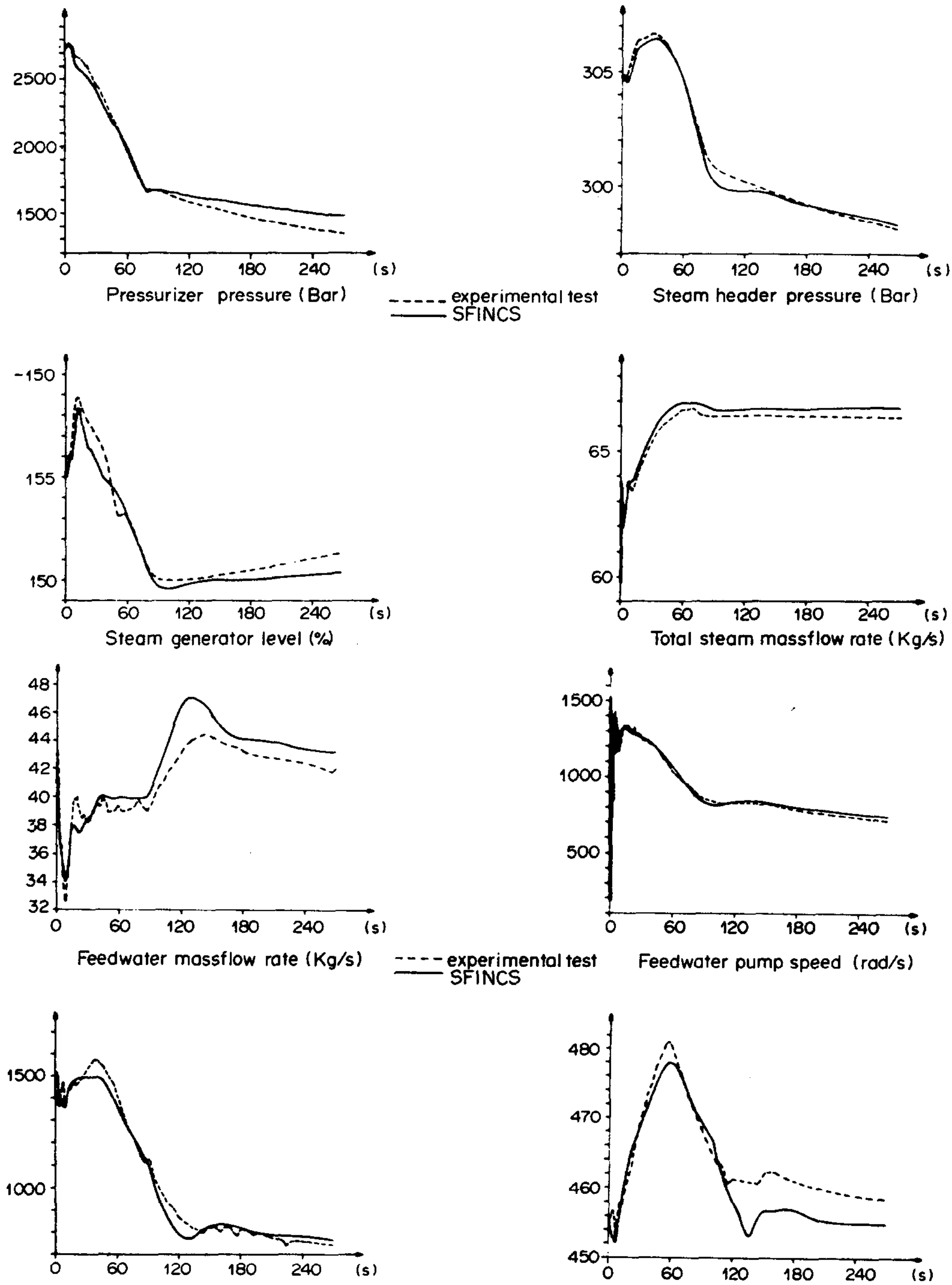

FIG. 2. Manual full-load rejection transient. SFINCS model responses compared to an experimental test.

systems must be accomplished using the same care applied to the process modelling.

Furthermore, it must be underlined that this comparison with a real power plant transient

allowed a significant tuning of the model control system parameters so that, a posteriori, the SFINCS model adapted to a French power plant can be considered a reliable simulation tool for operation procedure verification, such as the BABEL code in use at SEPTEN.

Exploiting the modularity of the LEGO package an Italian PWR power plant model has been set-up by updating the model mentioned above.

While the main topological modifications involved only the BOP circuit, all the geometrical data and regulation systems were updated for this purpose.

In order to verify the make-up of this new SFINCS model, some comparison tests have been made using STRIP as a reference model. STRIP is an Italian PWR power plant model developed at CRA using the modular EDF code SICLE (Maxant and Perrin, 1979); the Italian PWR program being in the design phase, at the present time STRIP is mainly used for components dimensioning dynamic verification (Busi et al., 1983).
As it has already been pointed out in the introduction, the experience of carrying-out some critical simulation studies showed the necessity of having an independent verification tool: the aim of the SFINCS model is to accomplish this task.

The comparison test between the SFINCS and the STRIP models presented here is a manual full-load-rejection transient shown in Fig.s 3 and 4.

This power plant operation procedure is the same as the one discussed above, but rod control and steam dump control system designs are different; as a result of this, following a load rejection, the Italian PWR plant reduces more quickly its nuclear power, thus obtaining a minimum load (5%) in ten minutes.
The most important difference that can be observed comparing SFINCS and STRIP responses is that the trend of power in SFINCS is higher than in STRIP.

A detailed analysis proved that the outflow coefficient of steam dump valves in SFINCS is computed in a different way from that of the STRIP model; this difference directly affects the computation of the total steam massflow rate, that is the equivalent of the thermal and nuclear power.
This fact has a general influence on the long-term system behaviour but doesn't affect in a significant way the quality of the results.

Another possible observation can be made with regard to the steam generator level; during the initial three minutes of the transient, STRIP model response denotes some oscillations that don't depend upon feedwater or steam mass-flow rate variations as shown in Fig. 4.

The more highly dumped level response of SFINCS is due to the intrinsic differences between the evaporating zone LEGO module and the corresponding SICLE module (Maffezzoni et al., 1983), (Maxant and Perrin, 1979).

During the last four minutes of the transient, the steam generator level of SFINCS shows an overshoot with respect to the STRIP response due to a more important feedwater massflow rate. This difference is correlated with the differences on steam generator pressure and feedwater turbo-pumps speed.
It is worth noticing that the SFINCS-STRIP comparison test presented here is significant because the simulation codes used, LEGO and SICLE respectively, are quite different in modelling and in numerical computation methods.

The general favorable agreement between model responses constitutes an important qualification of SFINCS as a reliable code for the simulation of the Italian PWR power plant of operation procedures.

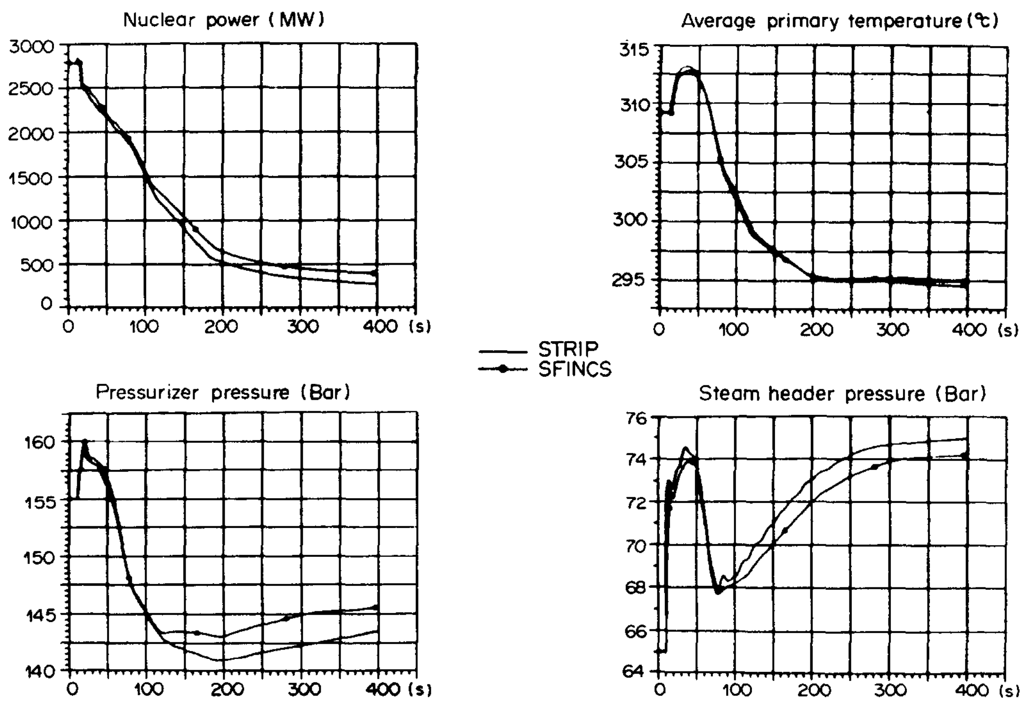

FIG. 3. Manual full-load rejection transient. SFINCS model compared to STRIP model.

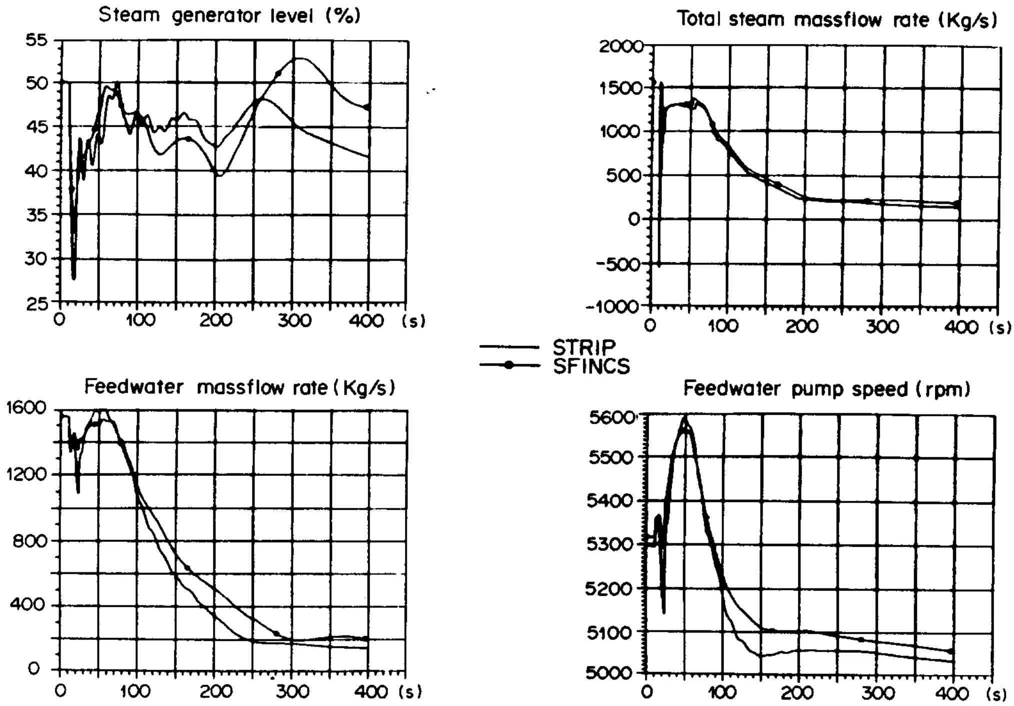

FIG. 4. Manual full-load rejection transient. SFINCS model compared to STRIP model.

CONCLUSIONS

The LEGO package has been validated and applied in several occasions on conventional oil-fired power plants. The results presented in this paper show that Lego modelling principles can be applied to the simulation of PWR power plant operation procedures. Modularity, reliability and numerical efficiency of LEGO, tested in carrying-out the SFINCS model validation, are important features that can be exploited in a modelling extension of the "modules library", thus allowing the setting-up of a simulation code for accidental transients analysis.

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